WATER[1]

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THE task of science is one that may be fulfilled quite directly by providing useful information of a practical sort for our immediate needs, or it may furnish us with general ideas which, if we are skilful enough and intelligent enough, we may use to explain a great variety of phenomena. These general ideas when combined make up our conception of the universe. The latter function of science is the more important one. It is the one that brings science close to philosophy. It is the one that arouses the greatest interest and enthusiasm in those who pursue the task of science. When we look for generalizations of this kind we always seek simple explanations of nature, confident that they may be used as guides to our action in particular cases and as means for gaining an ever increasing control of the world that we live in. Everything in the history of science justifies us in saying that it is the general interpretation of nature which, especially in the last hundred years, has given man his extraordinary increase in material power, an increase in power which he has used far from wisely no doubt, but which for better or for worse he possesses.

In the ancient world there were a certain number of advances of this kind. The history of geometry, in spite of the labors of the last century and in spite of Einstein, is to a great extent ancient history. The few necessary general conceptions that the Greeks found out enabled them to develop a complete science of geometry, enabled them to be good surveyors, enabled them to begin to understand how to lay out the heavens and the earth in their astronomy and in their geography, enabled them to see how to make buildings, and to do a great many practical things.

But in the main the really important, the really general ideas of science, are modern, and of course the most interesting ones have to do, at least so most people will think, not with static things, not with space taken by itself, but with dynamic things, with the question of what is happening in the world. On the whole, the most interesting and the most important generalizations of science

[1] This lecture was one of the public series given in Boston on Sunday afternoons recently under the auspices of the Harvard Medical School.

will be judged by most men to be those that tell them what is happening in the world, how things happen and how those happenings may be, if possible, changed to their own advantage, and how they may be interpreted so as to yield a philosophy.

Of course everyone knows that the first step in this direction in modern times, the first step of great importance, was the interpretation of the phenomena of our solar system. It was the labors of Copernicus, of Galileo, and of Newton that enabled men to look at the sun and the moon and the planets, and to think quite clearly and quite simply and without any sort of difficulty at all about what their movements and their apparent changes in position and in form indicated. But, once more, it is not so much our solar system as it is our own earth that interests us, and until we come down to the earth and examine the happenings on the surface of the earth we are necessarily a long way from those things that interest us most.

How shall we state abstractly what is happening on the earth? That is one of the great questions for science as well as for philosophy, for sociology, and for all the other intellectual activities of man. What is happening on the earth? Of course there are an indefinite number of answers to that question; but if we seek the strictly scientific answer of physical science I think there can be very little doubt that it is possible to put it in a few words which make our interpretation of the changes in nature surrounding us surprisingly simpler than they otherwise would be.

Men in antiquity and in all ages have vaguely perceived an answer to this question. Perhaps many of you have heard of the famous remark of Thales, who is often thought of as the founder of philosophy and mathematics and science, that water is the origin of all things. This statement seems to many people to-day, I suppose, ridiculous, or at all events very exaggerated, but it is in fact much less ridiculous and much less exaggerated than you may suppose. A little later Empedocles and Aristotle, extending the elements from one to four, included water along with earth, air, and fire as the elements of which the world is made up. No doubt the word "element" is used in a sense a little different from our ordinary idea of an element to-day, but we still speak of the Aristotlean idea when we talk about exposure to the elements. Of these elements water is in many respects the most interesting. Nevertheless, while it was always clear in antiquity, as it has been in modern times, that water is very important in the world that surrounds us, its real importance is a comparatively recent discovery.

In the first place, it was only a century and a half ago when

Cavendish and Watt and others first found out that water is not itself what the chemist now calls an element, but that it is a compound, a compound of hydrogen with oxygen, a substance that can be formed by burning hydrogen gas in air or in oxygen. With this discovery a new road was opened, not only for chemistry and for physiology, but for the general interpretation of nature. Even before that time men had begun to understand the meteorological cycle, to perceive that there is going on on the earth a physical process which may be very briefly described as the evaporation of water from the ocean, from lakes and streams, and from the moist land, its dissemination as water vapor throughout the atmosphere by the winds, its precipitation as rain and snow and hail and dew, its collection into streams, but not a rapid collection, for it persists for long periods of time in the soil and underground, and finally its return to the ocean and reevaporation. That had been perceived, as I say, quite clearly before the discovery of the chemical nature of water.

After that discovery another thing became apparent, that all that is happening in living organisms, in animals, and in plants on the earth, may be regarded in one sense as a part of this great meteorological cycle, this great cycle of water in its evaporation and condensation and flowing back through definite channels; for, as you know, our rivers persist, our streams persist, the circulation takes place in a very definite and very definitely canalized way. As I say, when men had made out the chemical nature of water they were able to see that water and carbonic acid are taken up by the plant, taken, if you will, out of the meteorological cycle and built up into sugar and starch, and then, sooner or later, turned into a great variety of substances, the substance of the plant, in short. These in turn serve as the food of the herbivorous animals, of cattle and sheep, and they are not greatly modified when built up into the body of the ox or the sheep. Next they may be consumed by man, or by a carnivorous animal, and are made over into the materials of his body. But sooner or later they are turned out into inorganic nature, excreted, as water and carbonic acid, after being burned in the body, once more to become a part of the meteorological cycle.

That, I submit to you, is a fair statement, which no doubt needs a great deal of enlargement, a fair statement in terms of physics and chemistry, of what is happening on the surface of the earth. What is happening on the surface of the earth is, first of all, a circulation of water, a circulation of water which we recognize in the fall of rain, in the flow of streams, which we recognize equally in the growth of plants and in the feeding of animals on plants,

and in the burning up of material in the body of the animal—of course a circulation of water and of other things, other things which in the total are very numerous and certainly very difficult to know in all cases, but fundamentally a circulation of water.

I have not touched upon the energy of the process, the side of the question that is represented by the energy that goes into the water to evaporate it off the surface of the ocean, that goes into the green leaf to turn water and carbonic acid into sugar and starch, or the energy that comes out again in the form of muscular activity and body heat in you as you live, when you convert starch, sugar, and other things formed from them in the plant, back to water and carbonic acid. But let us say in the beginning that what is happening on the surface of the earth is this circulation of water, and let us add that it is a circulation which is driven by the energy of the sun, which is driven both in the one cycle, in the meteorological cycle, by the sun's heat evaporating the water, and in the other, the organic cycle, by the sun's energy making possible the formation of sugar and starch from water and carbonic acid.

In the first place, this process depends upon the great amount of water that there is on the earth. There is enough, if the earth had a perfectly smooth surface, to cover the whole earth, to a depth of two to three miles. How much of this is circulating it is very difficult to say. The amount is large. For instance, at the Equator evaporation takes off a layer of perhaps about seven feet every year from the tropical ocean. Of course the evaporation is less in other localities, and it is much less where there are no great bodies of water, but that will perhaps give you some idea of the magnitude of the process.

How much is the energy involved in this process? How much work is done? How much energy of the sun does it take to evaporate so much water? A few square miles of the tropical ocean are taking up solar energy in the process of the evaporation of water to such an extent that if that energy were available in the bodies of the people of the United States, it would run all their bodies; that is to say, all the work that we are capable of doing, plus all the heat that we produce, is equivalent to an amount of energy which is no greater than that involved in evaporating the water off a very few, perhaps ten, square miles of the surface of the tropical ocean. So you see that not only is there a vast amount of water being evaporated, but that amount of water carries with it, involves in its evaporation, a prodigious amount of energy.

Another way of studying the process is to try to form an idea of the run-off of the rivers of the earth. It has been estimated that the run-off is yearly, for all the rivers of the earth, about 6,500

cubic miles of water; that is to say, if you were to take a band a little more than two miles wide from Boston to San Francisco, and imagine it to rise up one mile into the air, that would give you a solid equivalent to the volume of water that pours back into the oceans yearly. And that of course is only a fraction of the water that evaporates yearly, because a great deal that evaporates and falls to the ground never reaches the ocean at all.

This prodigious amount of water carries with it to the ocean what seems to be an almost equally prodigious amount of other material. There are something like 5,000,000,000 tons of dissolved substance in the river waters going back to the ocean yearly, and nobody knows how much undissolved sediment there may be. This dissolved material has been leached out of the earth, it is being leached out of the earth all the time, and the record of it is the accumulation of dissolved substances in the ocean as well as that long continued action of sedimentation which is on the whole the greatest of geological processes.

In the sea, as a result of this, nearly all the chemical elements are contained in solution, most of them, to be sure, in such small amounts that they can not be measured, but so many of them are there that the sea water is quite a different thing from anything else in the world, and can not be imitated. Nobody ever made an artificial sea water that would serve the purposes of sea water as an environment for simple marine forms, as well as sea water itself. You may make as careful an analysis as you please of the sea water. You may put into pure distilled water all the things that you can find in the sea water, and then if you try to make organisms live there they will not live in it—some of them, at least, will not—as well as they will live in genuine sea water.

There is a good deal of resemblance between the salts dissolved in our blood and the salts dissolved in sea water. This has led Quinton to speculate about the use of sea water for medical purposes. He has made many experiments by diluting it to the proper degree and injecting it into the body. It has been suggested by Professor MacCallum that our blood is, so to speak, descended from sea water, that in the course of evolution somehow or other the fluids of the body originated as sea water. Of course single-celled organisms have no blood. When multi-cellular beings came into existence, where did the fluid which bathes the cells come from, provided multi-cellular individuals did develop from the unicellular? It is not a wild assumption to suppose that sea water furnished the inter-cellular liquid, that it was the material that first surrounded the several cells making up the complex organism. If you look into the whole story of comparative physiology that

idea, while it must not be pushed too far, seems not an extravagant one, and if so, it is interesting to reflect that in that original simple fluid, simple compared with our blood in most respects, there were nevertheless a vast number of substances that had been leached out of the earth's crust in the course of millions of years.

This peculiarity of sea water depends upon the fact that water is, among all the liquids that we know, on the whole the best solvent, the one that can dissolve the greatest number and the greatest variety of substances of all kinds. That of course is a statistical statement. There are some things that water can not dissolve which can be dissolved by a great many other things; but by and large, taking everything that we know, taking all the chemical substances that we know, there is not anything which on the whole is a better solvent, or capable of dissolving a larger number of things, or greater quantities of them, than water.

Well, that is one of the very decisive facts in the meteorological cycle. It is one of the great factors in determining the geological action of water, in determining a large part of the evolution of the surface of the earth. And, on the other hand, in the organic cycle, in men, in animals, and in plants, water, always present in large quantities—your own body is three quarters water—contains a great number of things dissolved in it. This solvent action is certainly no less important in physiology than it is in geology.

Not only does the water in your bodies, the water in the blood, the water inside the cells, the water in the lymph, contain a great many things dissolved in it, but it is almost exclusively in solution that things penetrate into your body. That of course may seem to you a strange statement. You are well aware that you eat many more or less solid substances—anybody can swallow a lump of sugar, which is certainly a solid—but in fact what is geometrically inside your body is not necessarily physiologically inside your body. The digestive tube is physiologically not inside the body, and the process of digestion turns most substances that are swallowed in solid form into soluble products, which are dissolved in water and then in solution pass the real physiological barrier, the wall of the intestine, and so enter the body. This is no less true of the substances that are excreted from the body. The waste products are turned out of the body in solution, and if it were not possible to turn them out in solution it is very difficult to imagine by what kind of physiological device it would be possible to carry on the activities of really active bodies and get rid of the waste products that have been burned up in the course of their activity.

This great circulation of water has another very important influence upon the world, and upon the world of life, and that is

its effect upon climate. Every one knows how much more steady is the state of the weather on small islands at great distances from continents than in most other places. Every one knows how much milder the climate is, how much cooler in summer and warmer in winter, at the sea shore than a comparatively small number of miles inland. This phenomenon depends upon water.

How does it depend upon water? What is the effect that water exerts in that respect? Well, there are several factors. In the first place, it takes a great deal of heat to raise the temperature of water, or, as the physicist says, the specific heat of water is high. If you take, for instance, a pound of water and a pound of almost anything else—there are a few substances that are harder to heat than water—and heat them over a carefully regulated flame for a certain length of time, and measure the rise in temperature, you will find that the rise in temperature of the water is less than that of the other substance. As I say, there are a few exceptions, but there are very few. The result is that an ocean or a lake absorbs heat, and does not itself rise very much in temperature.

Again, the evaporation of water takes up heat. Every one knows that. Every one knows that in order to evaporate water away at all rapidly you must heat it, and the amount of heat that is taken up in this evaporation of water is greater than in the evaporation of anything else; that is to say, you have got to put more heat into water in order to boil away or to evaporate, let us say, a pound of it, than you have in order to evaporate a pound of anything else. Thus the more rapid the evaporation the more effective the resistance of water to the rise of temperature, and for that reason the cooler the climate in the marine region compared with the climate in a region where there is no water to evaporate. This is one of the most important of all economic factors on the earth. It is a factor that, as much as any other one, perhaps, determines whether a given part of the earth is or is not really favorable for a high and active and prosperous civilization.

But these factors are no less important in your own body than they are in determining the climate. As you know, you are constantly producing a considerable amount of heat, and that heat has somehow or other to be got rid of. If it were not, your body temperature would continue to rise. Well, in the first place, if your body were not mostly water, and therefore such that it takes a great deal of heat to raise its temperature one degree, a little exercise might be impossible. If it were not for the fact that it takes so much heat to raise the temperature of the body a little, on account of the presence of water as its principal constituent, if it took only that amount of heat which is necessary upon the average

to raise the temperature of most substances one degree, running a mile might be quite sufficient to produce a coagulation of all the albuminous material in the body, and therefore death.

That is to say, the regulation of the temperature of the human body rests first of all upon this fact: that you have to heat water so much in order to raise its temperature a little, and then, in the second place, upon the effect of evaporation. The effect of evaporation is to cool the body very much, because you have to put a lot of heat into water in order to evaporate it, and since evaporation is the only way of cooling the body when the temperature of the environment rises to the temperature of the body this is a matter of the first importance, as everybody knows from his own experience in hot summer weather. It is a priceless advantage in the economy of your body that so much heat is taken up in the evaporation of water during sweating.

One of the factors that greatly influence the circulation of water on the earth is the way in which it clings in the soil. Indeed water clings better, on the whole, than any other substance. This is due to the phenomenon which everybody has heard of as capillarity, and which is well illustrated by the action of a sponge in soaking up water. If you study this process you will find that it is easy to represent the sticking power of a liquid in the soil or in any finely divided matter by the height to which it can rise in a small capillary tube, in a very fine tube. Water rises to a very great height relatively to other substances in such a tube, and for the same reason it sticks very tight in the soil and water rises to a great height in the soil. That is one reason why great portions of the earth are habitable, or at least can grow crops. If water did not stick as well as it does, a large portion of the fertile earth would be sterile.

But here again we have come upon a property of water which is just as important in the body as it is in the meteorological cycle. The living cell may be compared to a microscopic swamp, to a swamp of inconceivably fine dimensions. There is water running through it, and it consists of a very intricate meshwork of only partly known nature. In this swamp—this microscopic swamp, if I may call it that—these same forces, these same capillary forces, are of decisive importance. And here again it is the particularly great capillary activity of water that is one of the factors that determine the nature of physiological processes.

There is one more point that I want to refer to about the inorganic, the meteorological cycle, because it is a particularly interesting and important one, although this one seems to have no highly important direct bearing upon our own bodies and our own

life process. What causes rainfall? It takes a good many things to produce a precipitation of rain, but we may begin at the beginning and say that at least you can not have rain falling out of the air unless the air has become supersaturated with water vapor. The way to bring about that condition is to cool air that is pretty moist, because the amount of water vapor that the air can hold varies with the temperature. For instance, if you go down to the freezing point, to 32 degrees Fahrenheit, the amount of water vapor when the air is quite saturated is almost exactly one half of the amount of water vapor that is in the air at about 50 degrees Fahrenheit. Suppose, then, you have air that is three quarters saturated at 50 degrees Fahrenheit. Cool it down to 32 degrees Fahrenheit and it becomes not three quarters but three halves saturated; that it to say, it has 50 per cent. more water than it can hold. That water will come out in the form of rain.

This difference, a difference of 100 per cent. in the amount of water vapor that the air can hold, is far greater than the difference in the amount of the vapor of any other substance that the air can hold. That is to say, if you had any other substance at 50 degrees Fahrenheit, any other substance whatever, and the air were just three quarters saturated with it, and you cooled it down just to 32 degrees Fahrenheit, then you would not have reached the saturation point and the vapor would not fall out.

If there were not this property, rain would be a comparatively rare occurrence. Moreover, unless rain falls, unless water comes out of the air, there can not be further evaporation, because you can only evaporate into air which is more or less empty, so far as the water is concerned; that is to say, the whole meteorological cycle, the circulation of water, depends upon the rate of precipitation quite as much as upon the rate of evaporation, and the rate of precipitation of water is great because of this property of water.

I think I have perhaps said enough to make clear to you something of the natural importance of water. Such are the reasons why it is possible to say that what is happening on the earth in the last analysis is a circulation of water and the results of that circulation. This is true not merely because there is a great deal of water on the earth, but also because water is a remarkable substance that has a good many unique peculiarities. But in discussing these properties, I have thus far spoken only about what may be called the physical peculiarities of water. Water is quite as important a substance chemically, and indeed I think we may say that the most important clues that we find in the properties of water to our understanding of what is happening in our every day life are to be found in the chemical properties of water rather

than in its physical properties. This leads us back to the great French chemist Lavoisier, the most eminent victim of the French Revolution and the man who perhaps made the greatest contribution to science of the eighteenth century.

Lavoisier, studying the process of burning, of combustion, of oxidation as we call it, discovered that when things burn they combine with oxygen. Those of you who are not chemists and who have not studied chemistry will of course always feel a certain discomfort when one talks about the union of atoms. Atoms can not be seen. They are hard to imagine. But somehow or other the burning of tin for instance or the burning of mercury, is the combination of one or more atoms of the one element with one or more atoms of the other element. Tin and oxygen combine to form the oxide of tin. The atoms somehow or other fasten themselves together. That is what Lavoisier found out. He did not express it in terms of atoms, but he saw that these elements combined. So it is in the case of the burning of hydrogen, and water is a compound of hydrogen with oxygen. Atoms of hydrogen, two in number, combine with one atom of oxygen to form H_2O, according to our present way of stating the case.

Well, having discovered the nature of combustion, Lavoisier turned to all kinds of cases where there was combustion. He proved, for instance, with Laplace, the great astronomer, in one of the most remarkable collaborations in the history of science, that in the last analysis our life activity, so far as it is chemical, is oxidation. The oxygen that we breathe into our lungs is combined with the various elements that make up our foods, and then the products are turned out as carbonic acid gas, which is nothing but the oxide of carbon, the result of burning carbon, and water.

Then, reflecting further upon this, reflecting not only upon the chemistry of the process but also vaguely upon the energy that was involved, so far as it could be represented by the heat of the process, Lavoisier saw the real nature of the process, Lavoisier saw the real nature of the organic cycle and stated it clearly. He perceived that plants draw from the air that surrounds them and from the mineral kingdom the necessary materials of their organization; animals take from the plants that which the plant has formed, directly in the case of the herbivorous animals, indirectly in the case of the carnivorous animals, and build it up into their bodies, and finally the processes of combustion, fermentation, and putrefaction are continuously returning to the inorganic world the materials that were taken up originally by the plant. Of course

these materials are not merely water, nor merely water and carbon dioxide, but also other substances.

But note this. In the organic cycle water and carbon dioxide are free; the other things are fixed. Those things that are free in the physical sense are also free in the economic sense, under a wide variety of circumstances. You don't have to pay, at least in New England and in many parts of the world, for the water and carbon dioxide which are the principal foods of the plant; all that you have to pay for are the so-called fertilizers, which make up an infinitesimal fraction of the material taken up by the plant. Indeed, if it were not for the mobility of water and carbon dioxide in this cycle that Lavoisier first understood, there would be no vegetation on the mountain tops. How could the material get there? The mountain tops would necessarily be bare. Not only the mountain tops, but everything would be bare except the waters of the earth. It is because water and carbon dioxide circulate, circulate rapidly and penetrate everywhere and stick when they get there, that there is a widespread vegetation, that there is an intense organic activity on the earth.

But now what of this process that goes on in the plant? Lavoisier could not understand it. It goes on in the green leaf, and the green leaf is truly the symbol of life. It is the starting point of life. It is the factory in which are created the materials of your body and mine, of the body of every living thing. These materials are created by the conversion of water and carbonic acid gas into sugar and oxygen through the influence of solar energy and with the fixation of that energy. Sunshine, water and carbon dioxide, if one may speak very loosely, are the components in the green leaf from which sugar or starch and oxygen are produced. The oxygen is turned out—the oxygen, please note, that had combined previously in your body with hydrogen and carbon in the burning that is the essential process of your own activity. In the leaf this process is reversed. The energy of the sun is fixed in the leaf, and that is the source of the driving force of your body and of the driving force of every animal body.

And not only that, it is the source of our fuels generally. If you will reflect for a moment, and remember that not only wood, but coal and petroleum, gasoline, what you will that is combustible upon this earth, is stored solar energy that has been fixed in the green leaf in the past, you will realize the extraordinary economic importance of this process. You will then realize that the cycle is, in fact, not only from the standpoint of the material changes, but also from the standpoint of energy, of horse power, of what you

must buy and pay for as a source of any sort of material activity, the decisive factor on the earth.

Since we can increase this process of photosynthesis, since there are still portions of the earth that are not adequately utilized, it is conceivable that one of the solutions of the problem of the increasing demand for energy may be to grow more available energy, for example, in the Amazon basin, where there are forests that it does not pay to cut at the present time. We might, for instance, turn a vast amount of solar energy that is not being utilized at the present time, or that is being expended in a manner that we can not ourselves turn to account into starch and sugar, into industrial alcohol, and so get a substitute for gasoline. That is an idea that has been in the minds of chemists, of course, for many years. One does not know how economic conditions will develop. At all events, we have here the clue to an understanding of the sources of energy on the earth. Aside from the fixation of energy in the organic cycle, and aside from the water power and other sources of energy in the inorganic cycle, there is little enough of any kind of energy that is available.

You might perhaps have expected me to say something about water in medicine, since this is a medical school lecture. Water is indeed important in medicine, but not, I suspect, in a manner that makes it possible for a lecturer to explain in two words its importance. There are diseases involving water. Of course dropsy involves the physiology of water in a remarkable degree. And there are processes that might be regarded as in a certan sense the opposite of dropsy, such as the curious dehydration of sick babies. In many cases they lose water, and it is difficult, or impossible, to get it back again. I can only say that perhaps because these are in some respects simple phenomena—I say in some respects—we know just enough about them to know that they are so complicated that it is really difficult to explain them or even to understand them at all.

And so I shall, I fear, have to omit the more practical and immediate bearings of the physics and chemistry of water upon the organism, especially under pathological conditions. It is the principal constituent of our bodies, it is the principal substance that enters our bodies, it is the principal substance that leaves our bodies, and it is, as I have said, that substance whose movement in the inorganic world and in the organic world constitutes the first, the most fundamentally important, activity in the world that we live in.